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Review of thermal cycles exploiting the exergy of liquefied natural gas in the regasification process

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ABSTRACT

In the present paper, a review is carried out of the current state of thermodynamic cycles that exploit the exergy released during liquefied natural gas (LNG) regasification, with the objective of improving power plant efficiency. A study of the exergy available in the LNG is carried out and is divided in thermal and mechanical exergy. The mechanical aspect can only be recovered through the direct expansion of LNG. As for the thermal aspect, power plants based on Rankine, Brayton, and Kalina cycles, as well as combined cycles and cycles with CO_2 capture are evaluated. The choice of proper cycle for a better exergetic use is linked with the quality of the heat source of the cycle. The Rankine cycle is most suitable when of low grade, while the Brayton is more appropriate when disposing of a medium or high grade heat source. When the temperature of the heat source is high, the combination of Brayton, Rankine and direct expansion is most favourable in order to obtain good efficiency. Also established is the selection criteria of the working fluids. Ethane and ethylene are put forth as the most suitable to operate with low temperature Rankine cycles and CO_2 with high temperatures. In the case of Brayton cycles, helium and nitrogen are those recommended.

Contents

1. Introduction . . . 781
2. LNG exergy . . . 782
3. Power plant structures to exploit LNG exergy . . . 783
 3.1. LNG direct expansion . . . 783
 3.2. Rankine cycle based power plants . . . 784
  3.2.1. Working fluid properties and selection criteria . . . 784
  3.2.2. Rankine cycles combination . . . 786
 3.3. Brayton cycle based power plants . . . 786
  3.3.1. Working fluid properties and selection criteria . . . 788
  3.3.2. Brayton cycles combination . . . 788
 3.4. Combined cycles based power plants . . . 789
 3.5. Kalina cycle based power plants . . . 791
 3.6. Power plants with CO_2 capture . . . 791
4. Existing regasification plants with LNG exergy exploitation . . . 792
5. Conclusions and future works . . . 792
References . . . 794

1. Introduction

To achieve sustainable development whilst protecting the environment, improvements in the efficiency of energy conversion are necessary, with a view to reducing CO_2 emissions. Global

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Nomenclature

cp	constant pressure heat capacity (kJ/kg-K)
cv	constant volume heat capacity (kJ/kg-K)
e	specific flow exergy (kJ/kg)
h	specific enthalpy (kJ/kg)
p	pressure (bar)
q	specific heat (kJ/kg)
s	specific entropy (kJ/kg-K)
T	temperature (°C)
v	specific volume (m^3/kg)
w	specific work (kJ/kg)

Subscripts

0	reference ambient conditions
c	compression
p	pressure
th	thermal
s	storage conditions

Acronyms

ASHRAE	American Society of Heating, Refrigerating and Air Conditioning Engineers
BC	Brayton cycle
CFC	chlorofluorocarbon
GWP	global warming potential
HCFC	hydrochlorofluorocarbon
LNG	liquefied natural gas
NG	natural gas
ODP	ozone depletion potential
ORC	organic Rankine cycle
RC	Rankine cycle

electricity demand will increase by 70% between 2010 and 2035, according to the World Energy Outlook 2012 report produced by the International Energy Agency [1]. The European Union, however, proposes 20% reduction CO_2 emissions by 2020. Natural gas (NG) is considered as the dominant fossil fuel among a vast diversity of power sources, because of its lowest environmental impact during its life cycle, owing to its high hydrogen–carbon ratio in its composition. It is considered as a green fuel [2–4] and for purposes of transporting and storage, must be liquefied by cryogenic refrigeration, thus obtaining liquefied natural gas (LNG). Consequently, the LNG industry has developed rapidly in recent years. LNG is stored at a cryogenic temperature of approximately −165 °C and at a pressure marginally above atmospheric, in tanks specially designed to withstand such conditions [5]. To obtain LNG, a substantial amount of energy is needed, 1370 kJ/kg/s of LNG, according to calculations made by Khan and Leen in Ref. [6]. LNG, therefore, has high physical exergy, owing to low temperature along with its high quality chemical energy. However, LNG must be regasified in receiving terminals before being distributed to the end users of gas. This vaporization process releases a significant amount of cold exergy, of around 370 kJ/kg/s of LNG.

With conventional regasification systems, this exergy is transferred to sea water or another working fluid as the heat source. There can be considered to be three conventional gasification systems:

– Open rack vaporizers (ORV) with sea water [7–9].
– Submerged combustion vaporizers (SCV) [10,11].
– Vaporizers that use air as a heat source [12].

All the above systems require the use of power. What is more, with regards to sea water vaporizers, there are environmental restrictions in place that prevent seawater being cooled more than 3 °C in the Mediterranean Sea and 5 °C in the Atlantic [13], resulting in very large flows of water and hence electricity consumption for pumping needs. Due to the rising cost of energy, environmental restrictions and fuel savings, there is an evident need to recover LNG exergy during its regasification process.

This review is focused on the exploiting of exergy in the LNG regasification process to enhance the efficiency of thermal power plants. Extensive literature exists in relation to this topic, yet most publications deal with individual cases of cycles and there are hardly any references that carry out a review of most of the known cycles. Therefore, this article aims to give an overview of the alternatives available to take advantage of LNG exergy in power plants.

The paper is organised as follows: Section 2 analyses the exergy available in LNG, Section 3 studies and discusses the different thermodynamic cycles with LNG exergy exploitation. The selection criteria of the working fluids based on their physical properties are also set out. To end the article, Section 4 gives a brief review of the current cryogenic thermal energies, followed by the conclusions of the study.

2. LNG exergy

Exergy is defined as the maximum theoretical work obtainable from a system in disequilibrium with the reference environment. The reference environment is understood as a simple compressible system whose conditions are kept constant and uniform at a pressure of (p_0) and temperature (T_0), which in this case are considered to be $T_0 = 25$ °C y $p_0 = 1$ bar.

The exergy available in the LNG is considered to be entirely chemical and physical in nature, since the kinetic and potential aspects are neglected because of its little significance compared to previous ones. The study of the LNG exergy will focus on the physical aspect, as a result of being the only one useable during the LNG regasification process. Physical exergy is due to an imbalance caused by the difference in temperature and pressure with respect to T_0 and p_0.

When LNG is heated from its storage state (T_s, p_s) to the condition of equilibrium with the reference environment, the maximum work obtained in this process can be determined by the equation of energy conservation, expressed as:

$$\delta w_{\max} = \delta q - \delta h = T_0 ds - dh \tag{1}$$

By definition, the specific flow exergy is the maximum work that a flowing stream of matter can produce when evolving to the conditions of equilibrium with the environment, thereby fulfilling:

$$e = h - h_0 - T_0(s - s_0) = \int_{T_s}^{T_0} cpdT - \int_{T_s}^{T_0} cp\frac{dT}{T} - T_0 \int_{ps}^{po} \left(\frac{\partial v}{\partial T}\right)_p dp \tag{2}$$

where the first two terms are a function of temperature and the latter is a function of pressure. Thus, Eq. (2) shows that the LNG physical exergy has two components: a thermal and a mechanical component. The thermal exergy is termed as cold exergy and the

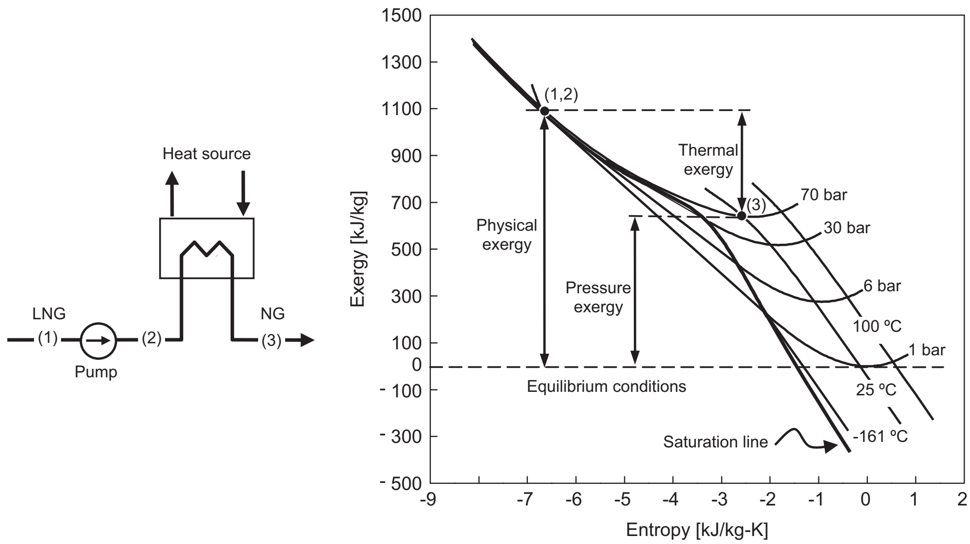

Fig. 1. Exergetic evolution of LNG during regasification in the exergy–entropy diagram.

Table 1
Required pressure for several uses of NG.

Use	Pressure (bar)
Steam power stations	6
Combined cycle stations	25
Local distribution	30
Long distance distribution	70

mechanical as pressure exergy. Therefore, the physical exergy of LNG is

$$e(T,p) = e_{th} + e_p \quad (3)$$

where

$$e_{th} = e(T,p) - e(T_0,p) \quad (4)$$

$$e_p = e(T_0,p) - e(T_0,p_0) \quad (5)$$

Fig. 1 shows the exergy development of the LNG during the regasification process in an exergy–entropy diagram. In order to simplify the analysis, the LNG is assumed to be pure methane. Point (1) represents the exergy in the tank storage conditions corresponding to -165 °C and 1.3 bar. In (2), the LNG has the NG distribution pressure to end consumers, which depends on the characteristics thereof. Table 1 shows the required pressure of the NG depending on usage [14].

In passing from point (1) to (2), the increase in LNG exergy is owed to the pump work, but it is hardly detected because of being in the subcooled liquid area. Assuming a distribution pressure of 70 bar, the exergy increases when moving from (1) to (2) in approximately 11 kJ/kg. Point (3) corresponds to the NG exergy in the distribution conditions, which in the case of Fig. 1 are considered as 5 °C and 70 bar.

Before being vaporized in a heat exchanger, LNG has a physical exergy of 1113.08 kJ/kg which corresponds with the exergy at point (2), of which 472.86 kJ/kg is thermal exergy and the difference is the mechanical exergy, respectively, representing 42.48 and 57.52%.

It is deduced from Fig. 1 that only 42.48% of the physical exergy can be exploited, since the rest is the pressure exergy required for the gas distribution process. Clearly the lower the distribution pressure, the higher the percentage of thermal exergy and therefore the more effective the use of LNG physical exergy. If the required pressure of NG is of 6 bar, exergetic exploitation is of 74.86%.

3. Power plant structures to exploit LNG exergy

LNG exergy can be extracted in several ways, just as in the process of liquefaction and air separation [15–18], in the food industry for storing and freezing foods [19,20], in seawater desalination [21,22], in household air conditioning [23,24], and industrial processes such as petrochemicals [25,26], etc.

However, in recent years, the most widely studied application to exploit LNG exergy is that of improving power plant efficiency, using LNG as a heat sink and as a contributor of additional exergy. Five general types of thermal power plants, based on direct expansion, are established. These are Rankine cycles (RC) [27–30], Brayton cycles (BC) [31,32], combined cycles [33–35], Kalina cycles [36,37] and cycles with CO_2 capture [38]. To follow is an analysis and discussion of and the different types of plants.

3.1. LNG direct expansion

LNG expansion in an open cycle as depicted in Fig. 2, besides being the most straightforward way of exploiting LNG exergy, is the most inefficient method of all. LNG is pumped at a higher pressure than the distribution pressure of NG and is vaporized and heated by a heat source, which may be the environment or residual heat. Then, the NG expands to transform NG mechanical exergy into electrical energy via an expander coupled to an electrical generator. This method is inefficient because during the vaporization and heating process, which, in the case of Fig. 2 is to 20 °C, almost all the LNG thermal exergy is yielded to the heat source and only the mechanical exergy is exploited when passing from high pressure to that of distribution [39]. To illustrate the example of Fig. 2, the high pressure of 270 bar was set as it was the highest value found in literature, obtained from Ref. [40]. In this case, the exploited exergy corresponds with the variation in exergy between points (3) and (4) and represents 11.75% of the LNG exergy in the storage conditions, point (1). It must also be highlighted that at the output of the expander, the NG must always be reheated to the temperature of distribution.

The direct expansion of LNG, as a unique method, is of limited use due to its low efficiency. Typically, this method is combined with the Rankine and Brayton cycles.

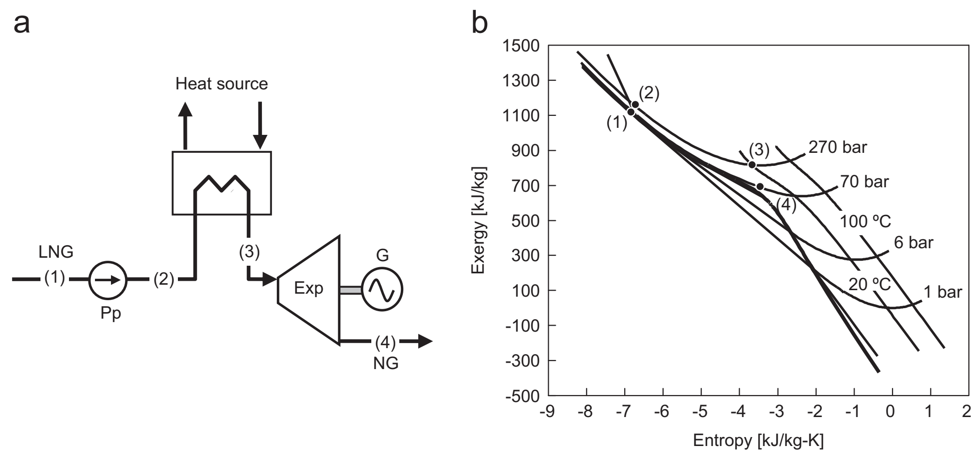

Fig. 2. Direct expansion of LNG: (a) basic structure of the open cycle, (b) exergy–entropy diagram. Exp: expander; G: generator.

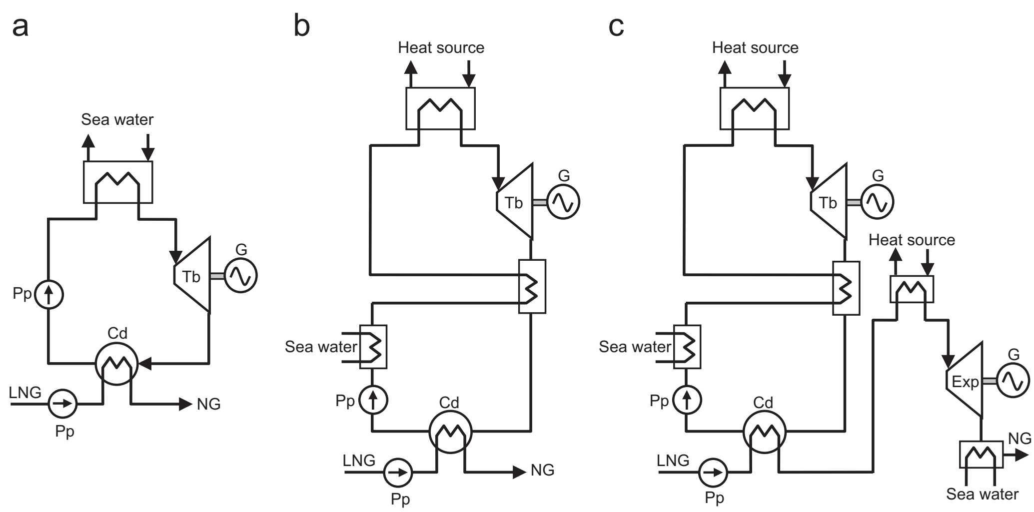

Fig. 3. Schematic configurations of the RC: (a) basic RC, (b) regenerative RC, (c) regenerative RC and direct expansion. Cd: condenser; Exp: expander; G: generator; Pp: pump; Tb: turbine.

3.2. *Rankine cycle based power plants*

In the RCs based power plants, the LNG cold exergy is used for cooling the condenser. During the process of LNG regasification, the thermal exergy released during vaporization and the heating of NG is used to condense the working fluid. Low temperature condensation can improve cycle efficiency due to the decrease in turbine back pressure. In the condensation process, it occurs simultaneously transfer of exergy in the direction of LNG→working fluid and energy transfer in the opposite direction.

Three RC based configurations are shown in Fig. 3. Fig. 3(a) depicts the schematic diagram of a simple RC. The heat source can be ambient heat, seawater, which is most common because of the location of regasification plants near the coast, or to increase efficiency by means of a heat source that is of higher temperature than the ambient. In this respect the options are very diverse; for example: solar energy [41–44], flue gases from incineration plant waste [45], residual heat derived from an industrial process [46] or cells including solid oxide fuel cells [47]. In these cases, some simple modifications can be applied to the basic cycle shown in Fig. 3(a) to achieve greater efficiency, such as those carried out in Fig. 3(b). One way is to install a regenerator at the turbine outlet for heating the working fluid before receiving heat from the external source. With the effect of the regenerator, the heat dissipated in the condenser is also reduced, thereby achieving to increase the mass flow ratio between the working fluid of the RC and LNG, increasing of the cycle's specific power by kg/s of regasified LNG. Another option to increase efficiency is to place a heater with sea water between the pump and the regenerator. Such options are analysed by Angelino and Invernizzi in [48].

In the two above configurations of the RC, only the thermal exergy from the LNG is used in the process of condensating the working fluid. To also recover the mechanical exergy, the RC is combined with the LNG direct expansion method, as shown in Fig. 3(c) [28,49,50]. The LNG, after passing through the condenser and in gas state, is heated by a residual heat source, which, in the event of not disposing of this, can also be seawater.

3.2.1. *Working fluid properties and selection criteria*

The working fluid plays a key role in the cycle. It must possess physical properties that respond to the RC application and an adequate chemical stability in the desired temperature range. The fluid selection criteria are based on the operating conditions, environmental impact, toxicity and flammability level, system efficiency and economic viability.

Resulting from an initial selection, and based on their property of condensing at low temperatures and environmental impact, 17 working fluids are proposed as potential candidates. The physical properties and safety and environmental data of these

Table 2
Physical, safety and environmental data for the working fluids RC.

Working fluid	Critical point		Range of applicable temperatures, (°C)		Normal boiling point (°C)	ODP	GWP (100 years)	Lifetime (years)	Safety group
	T (°C)	p (bar)	Minimum	Maximum					
Carbon dioxide CO_2	30.98	73.77	−56.56	1726.85	–	0	1	95	A1
Ammonia NH_3	132.25	113.33	−77.65	426.85	−33.59	0	0	days	B2
Ethane C_2H_6	32.17	48.72	−182.78	401.85	−88.82	0	5.5	< 1/2	A3
Ethylene C_2H_4	9.20	50.12	−169.16	176.85	−103.77	0	3.7	Days	A3
Butane C_4H_{10}	151.98	37.96	−138.26	301.85	−0.49	0	4	Days	A3
Propane C_3H_8	96.74	42.51	−182.62	351.85	−42.11	0	3.3	< 1/2	A3
Propylene C_3H_6	91.06	45.55	−185.20	301.85	−47.62	0	1.8	1.5	A3
Trifluoroiodomethane CF_3I	123.29	39.53	−153.15	146.85	−21.85	0	< 1	Days	A1
R116 C_2F_6	19.88	30.48	−100.05	151.85	−78.09	0	12,200	10,000	A1
R125 C_2HF_5	66.02	36.18	−100.63	226.85	−48.09	0	3,400	29	A1
R134a $C_2H_2F_4$	101.06	40.59	−103.30	181.85	−26.07	0	1,100	14	A1
R143a $C_2H_3F_3$	72.71	37.61	−111.81	376.85	−47.24	0	4,330	52	A3
R152a $C_2H_4F_2$	113.26	45.17	−118.59	226.85	−24.02	0	120	1.4	A2
R218 C_3F_8	71.87	26.40	−147.70	166.85	−36.79	0	8,600	2,600	A1
R23 CHF_3	26.14	48.32	−155.13	201.85	−82.09	0	12,000	270	A1
R32 CH_2F_2	78.10	57.82	−136.81	161.85	−51.65	0	550	4.9	A2
R41 CH_3F	44.13	58.97	−143.33	151.85	−78.31	0	97	2.4	

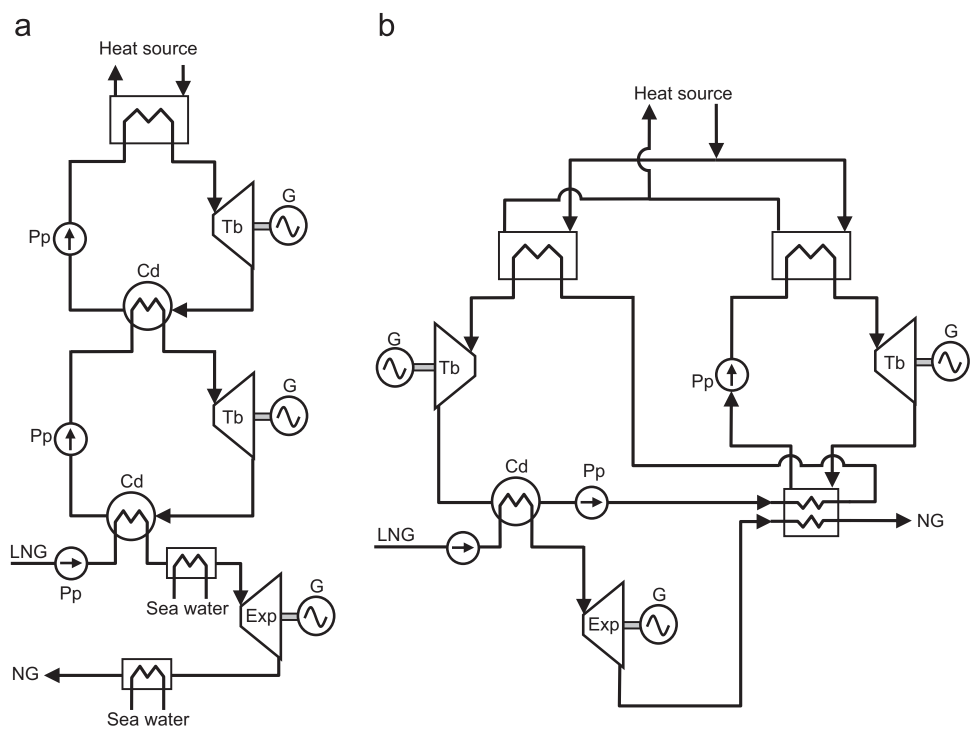

Fig. 4. Schematic configurations of RCs: (a) binary cycle and direct expansion, (b) RCs with equal high temperatures and different condensation temperature. Cd: condenser; Exp: expander; G: generator; Pp: pump; Tb: turbine.

fluids [51–54] are shown in Table 2, short listed for applying to RCs associated with the LNG regasification process.

The optimal characteristics of the working fluids for this application are:

– Low freezing point and thermal stability at high temperatures: the freezing point represents the minimum application temperature. Also, the vaporization temperature at atmospheric pressure must also be taken into account, defined as the normal boiling point. This temperature will be considered for the RC operating conditions. It is not recommendable to work with lower temperatures than those corresponding to the normal boiling point as this implies condensation pressures below atmospheric pressure. This prevents the possibility of air entering the circuit, thereby preventing the freezing of air moisture and flammable mixtures being generated in the event of using a flammable fluid.
The temperature of the available heat source will be taken into account to select the fluid according to its chemical stability at high temperatures, representing its maximum application temperature. In this respect, CO_2 is the most versatile fluid since it can withstand very high temperatures and can be condensed up to −50 °C, respecting a safety margin with its freezing point.
However, in cases in which sea water is used as a heat source, ethane and ethylene are frequently used, due to their low

normal boiling point and because there is a sufficient safety margin in relation to their maximum application temperature [55–57].

– High specific heat and low specific volume: a working fluid with such characteristics has greater energy absorption capacity thus reducing the mass flow required per kg/s of LNG as well as the installation size and pump consumption.
– Low environmental impact: the main parameters to measure the environmental impact of the fluid are the ozone depletion potential (ODP), the global warming potential (GWP) and the atmospheric lifetime. Due to environmental limitations, chlorofluorocarbon (CFC) and hydrochlorofluorocarbon (HCFC) fluids have not been taken into account.
– Safety: as an indicator of the fluid hazard level, classification according to ASHRAE (American Society of Heating, Refrigerating and Air Conditioning Engineers) is used. In general, the working fluid must not be toxic, flammable or corrosive, but these features are not always practically feasible. Many substances, such as ethanol or R143a, are considered flammable but this is not a problem when working with a safety margin with respect to the auto-ignition temperature.
– Readily available and low in price: CO_2 is a fluid that best meets this characteristic because it is naturally abundant [58].

All working fluids shown in Table 2 are pure substances. However, zeotropic mixtures, that possess variable pressure condensation and vaporisation process, may also be used in RCs. The effect of variable temperature in vaporization allows maintaining a temperature profile closest to the heat source temperature. The advantage of this is that the irreversibilities in the heat transfer are reduced compared to pure working fluids [59,60]. Therefore, it can be said that zeotropic mixtures make better use of the heat source exergy.

One of the most used binary zeotropic mixtures is ammonia–water. In [46], Wang et al., analyse an ammonia–water RC with an ammonia mass fraction of 70%. The cycle is associated with LNG regasification and the high and low temperatures are respectively 190 and −47 °C. Miyazaki et al. [45], also make use of the ammonia–water RC but elevate the high temperature to 300 °C. Another binary mixture, also applied in RCs, is composed of methane and ethane, used by Hua Xiong in a proportion of 65–35%, respectively, in Ref. [61].

3.2.2. Rankine cycles combination

When the heat source power supply is conducted at high temperatures, a single RC is not the most effective technique from the thermodynamic viewpoint. Most working fluids that allow the recovery of the LNG exergy at low temperatures do not have a high working temperature. Combined cycles are used in order to exploit the availability of operating with high temperatures to maximise efficiency as shown in Fig. 4. Binary cycles are characterised by employing the top cycle condenser as a heat source for the bottoming cycle. The top cycle can be operated with steam, (most common), ammonia or ethane, while the bottoming cycle requires a fluid with a low vaporization point such as butane, propane, propylene, ethane, or ethylene. In Ref. [62] Oliveti et al., propose the association of a waste incineration plant as an energy source, and a steam-ammonia binary cycle with direct expansion of LNG, as shown in Fig. 4(a). Other examples of binary cycles can be seen in [48], where steam and butane fluids are used and in [14,63], where a complex cascade installation comprising three RCs is proposed. In the latter case, the intermediate cycle has the upper cycle as the heat source and the lower cycle vaporizer as the sink. As working fluids, steam is used in the top cycle, propane in the intermediate and methane in the bottoming cycle, which is condensed by the LNG in the regasification process.

Another RC based configuration is presented in Fig. 4(b). In this case, the two RCs have the same peak temperature but a varying condensation temperature, depending on the cycle working fluid. Xiangyu et al. in [64], analyse this cycle configuration, adapting a metal hydride heat pump system as the heat source. A mixture of ethylene–propane is used as the heat source in the first Rankine with respect to the LNG step, and in the second ammonia–water.

Table 3 provides a summary of some citations that employ RC based methods for LNG exergy recovery.

3.3. Brayton cycle based power plants

In BCs, the LNG thermal exergy is used to cool the gas at the compressor inlet, causing a sharp drop in the specific compression work. This decrease is because the compression work is related to the specific volume of the gas, through the following equation:

$$w_c = \int_1^2 v dp \tag{6}$$

Fig. 5 schematically represents the four options available for the exploitation of the cold exergy in the BCs. The first, Fig. 5(a), corresponds to a gas open cycle in which the LNG cools the air at the compressor inlet. This application is studied by Kim and Ro [68] in a combined cycle in which the own LNG consumption of the cycle is used to cool the air at the compressor inlet during

Table 3
Summary of different RC for the use of the exergy of LNG.

Cycle type	Working fluid	Heat source	T max (°C)	T min (°C)	p NG (bar)	Thermal efficiency	Exergy efficiency	Ref.
Transcritical RC	CO_2	Solar energy	65	−10	7.0	8.48%	–	[41]
Regenerative RC+direct expansion	R143a	Solar energy	75	−60	6.0	22.33%	10.62%	[44]
RC+direct expansion	Ammonia (70%)–water (30%)	Refuse incineration	300	−40	4.0	29.00%	30.00%	[45]
RC	Ammonia (70%)–water (30%)	Waste heat	190	−47	3.8	–	25.88%	[46]
Regenerative RC+sea water heater	CO_2	–	600	−50	–	51.00%	–	[48]
Regenerative RC	Ethane	Sea water	−6	−88	30	–	11.50%	[57]
Binary cycle	Steam–butane	–	550	−50	–	52.30%	–	[48]
Binary cycle+direct expansion	Steam-ammonia	Waste incinerator	400	−50	80	42.50%	39.48%	[62]
Cascading 3 RCs+direct expansion	Steam–propane–methane	Flue gas	527		4	–	57.20%	[14]
Three-stage cascade RC	Propane	Seawater	10	−42	60	12.50%	65.20%	[65]
Supercritical regenerative RC	Propane	–	315	−42	–	33.50%	–	[66]
Supercritical regenerative RC	Butane	–	315	−1	–	24.10%	–	[66]
RC+direct expansion	Propane	Seawater	5	−39	70	6.00%	–	[67]

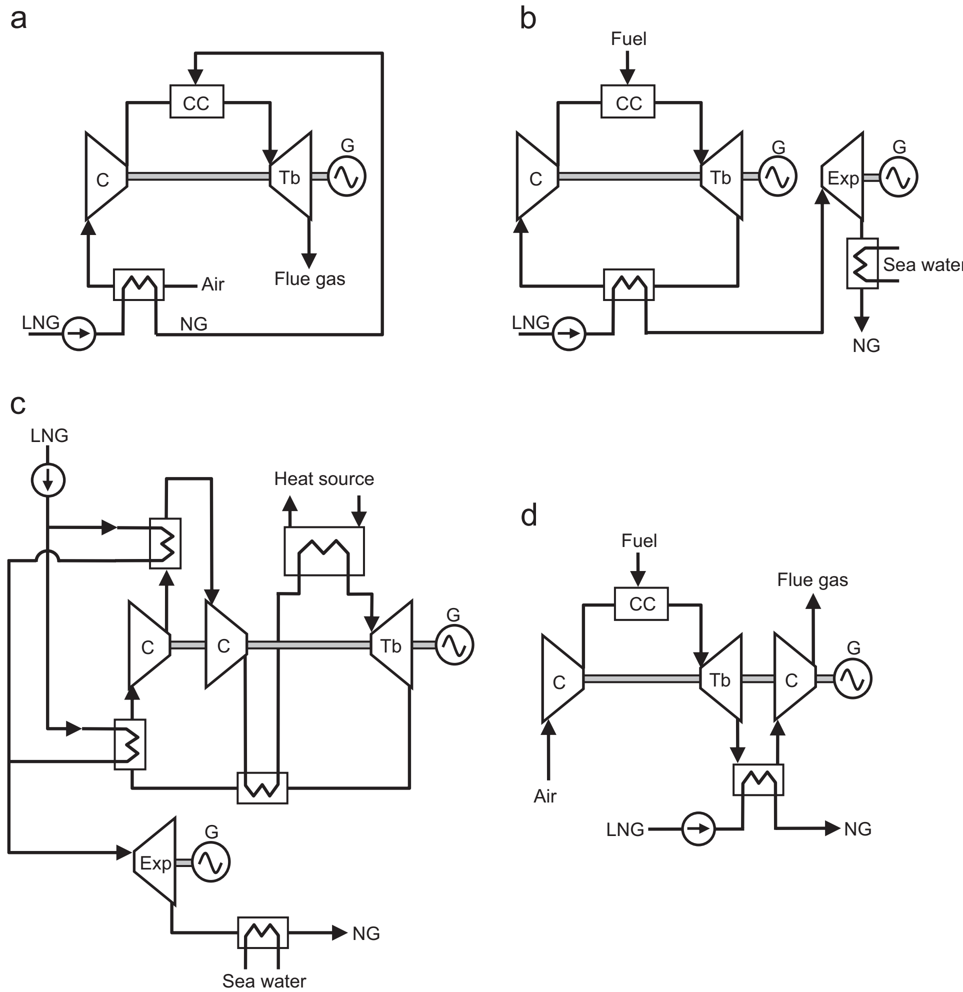

Fig. 5. Schematic configurations of the BC: (a) cooling air inlet in the gas cycle, (b) closed BC and direct expansion, (c) closed BC with intercooling, (d) post cooling open cycle. C: compressor; CC: combustion chamber; Exp: expander; G: generator; Pp: pump; Tb: turbine.

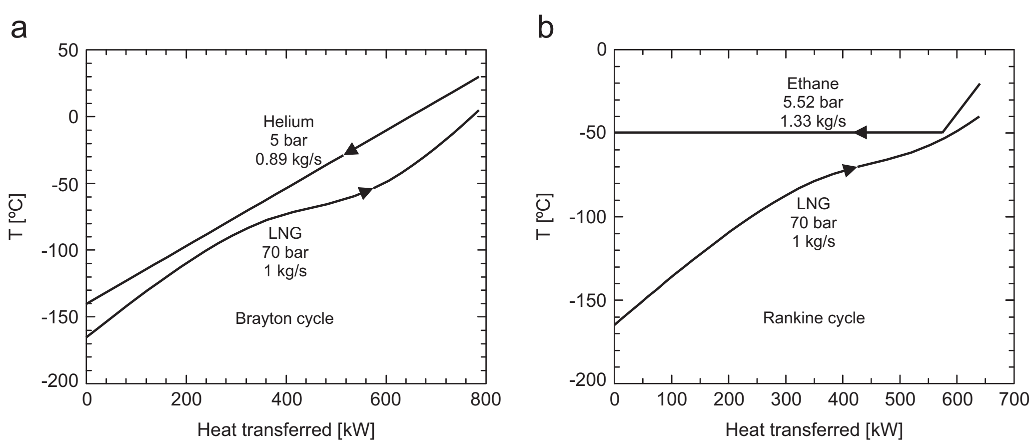

Fig. 6. Heat transfer between the LNG and working fluid in the case of: (a): BC, (b): RC.

warm seasons. An increase of 10 °C in the environment temperature above the compressor's design temperature causes a reduction in power of about 6%, of which 4% corresponds to the decrease of air mass flow and the remainder 2% corresponds to the increase of specific compression work. Kim and Ro found that the air temperature drop in the cooler with LNG depends on the environment temperature and relative humidity.

It is shown that by applying this system, the power increase is of over 8% in dry air conditions and of 6% under humid air conditions (60% relative humidity). The cooling of air may also be done through an intermediate heat transfer fluid (glycol) between the LNG and the intake air, as shown in Ref. [66].

In closed BCs, as shown in Fig. 5(b), the gas at the compressor inlet can be cooled to cryogenic temperatures [31,69,70]. Unlike the RCs, in the BC the LNG thermal exergy only becomes sensible heat from the gas. This fact allows the T-(Heat transfer) curves of the LNG and the BC working fluid to be closer together, thus reducing the irreversibilities in the heat transfer between both

fluids and increasing the exergetic efficiency of the process. Fig. 6 shows the temperature profiles in the LNG regasifier when either using a Brayton or Rankine cycle.

If the heat source is the environment (water or air) or another low-grade heat source, the RC is most suitable, whereas the BC is best suited when a medium or high grade heat source is available. This is because the RC compresses the working fluid in liquid state with a pump and the BC compresses it in a gaseous state with a compressor which absorbs more power. However, when the heat source allows working with high temperatures, the BC performs better because the working fluid of these cycles can operate at higher temperatures than in the case of RCs.

Bisio and Tagliafico in [14] also propose, with the aim of decreasing the compressor work, a two-stage compression with LNG intercooling, as shown in Fig. 5(c).

An open BC, unlike those described so far, is shown in Fig. 5(d) and is termed a mirror gas-turbine [71]. In this type of cycle, the LNG is used to cool the turbine exhaust gases, thus increasing the specific work thereof. With this technique, 27% of the exhaust gas energy can be converted into useful work [71].

3.3.1. Working fluid properties and selection criteria

The working fluids for closed BCs should be stable at high temperatures, have a low critical temperature, be ideally below the temperature of the LNG, non-toxic, non-corrosive, non-flammable and readily available at a reasonable cost. Table 4 indicates a number of substances which, in principle, could be used in such cycles. The substance data is collected from the NIST [51].

The most important property when choosing the fluid is the critical point conditions. The lower the critical temperature, the better, as this means working with temperatures close to LNG. Furthermore, the closer the cycle operates to the critical point, the better the performance achieved [72]. This is because as operating conditions move away from the critical point, constant pressure lines in a T-s diagram have a steeper gradient, increasing the compression work.

Another important fluid datum is its specific heat. The higher the latter, the better, as it reduces the fluid mass flow per kg/s of LNG, thus allowing a less bulky plant design. As for the specific heat ratio (cp/cv), it is advantageous to be the highest possible because the higher the specific heat ratio, the lower the compression ratio of BC operation [73], thus achieving a simpler plant design.

From all of the above, helium and nitrogen are presented as the most appropriate fluid for the combination of BCs and LNG regasification. What is more, air and oxygen can be ruled out for presenting risks of explosion if NG leaks in the heat sink.

3.3.2. Brayton cycles combination

The most frequent combination among the BCs is the use of a closed intermediate cycle in the top part of an open combustion cycle and direct expansion of the LNG at the bottoming part,

Table 4
Physical data for the working fluids BCs.

Working fluid	Critical point		Range of applicable temperatures (°C)		cp[a] kJ/(kg-K)	k[b] $= cp/cv$
	T (°C)	p (bar)	Minimum	Maximum		
Helium	−267.95	2.27	−270.97	1226.90	5.1930	1.6665
Nitrogen	−146.96	33.96	−210.00	1726.90	1.4013	1.4013
Argon	−122.46	48.63	−189.34	1726.90	0.5215	1.6695
Air	−140.62	37.86	−213.40	1726.90	1.0065	1.4017
Oxygen	−118.57	50.43	−218.79	1726.90	0.9196	1.3966

[a] Constant pressure specific heat at 25 °C and 1 bar.
[b] Specific heat ratio at 25 °C and 1 bar.

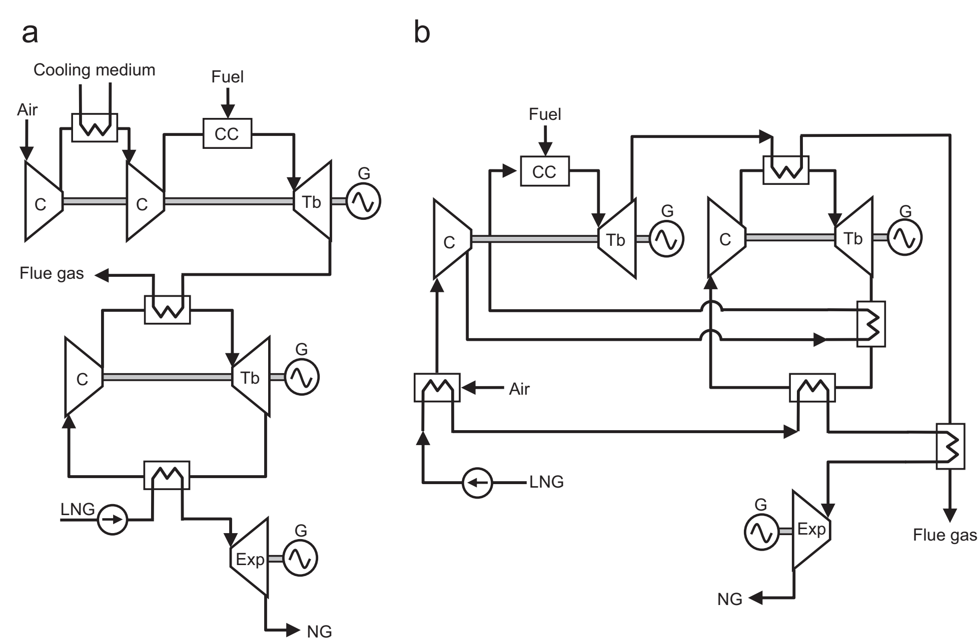

Fig. 7. Schematic configurations of combined cycles consisting of: (a) gas open cycle with intercooling, closed BC and expansion direct, (b) gas open cycle with cooling inlet air, regenerative closed BC and direct expansion. C: compressor; CC: combustion chamber; Exp: expander; G: generator; Pp: pump; Tb: turbine.

Table 5
Summary of different BCs for the use of the exergy of LNG.

Cycle type	Working fluid	Heat source	*T* max (°C)	*T* min (°C)	*p* NG (bar)	Thermal efficiency	Exergy efficiency	Ref.
Regenerative BC with intercooling + direct expansion	N_2	Flue gas	320	−140	15	–	45.94%	[14]
Regenerative BC	N_2	–	600	−120	–	63.00%	–	[72]
Regenerative BC	Argon	–	600	−120	–	58.00%	–	[72]
Mirror gas-turbine + direct expansion	Flue gas	Combustion heat	1500	0	20	55.50%	60.00%	[71]
Open cycle + BC	Flue gas—He	Combustion heat	–	−129	–	69.00%[a]	51.00%	[75]
Open cycle + BC + direct expansion	Flue gas—N_2	Combustion heat	1290	−141	80	75.50%	52.60%	[76]
Open cycle + BC + direct expansion	Flue gas—N_2	Combustion heat	1477	5	24	73.72%	67.66%	[77]

[a] Considering thermal efficiency combined heat and power.

thereby exploiting the LNG thermal exergy in the closed BC and the mechanical exergy in the direct expansion of the LNG. Two configurations of such cycles are shown in Fig. 7. Dispenza et al. in [74,75] propose only combining one open gas cycle at the top part and a closed BC at the bottoming. They analyse this combined cycle using helium and nitrogen, concluding that higher exergetic efficiency is achieved by using helium under a compression ratio lower than for nitrogen.

The combined cycle configuration illustrated in Fig. 7(a) is posed by Morosuk and Tsatsaronis in [40,76] and Morosuk et al. in [77]. In the three abovementioned references, an advanced exergy analysis is proposed to determine and divide the exergy destruction in each component in their unavoidable, avoidable, endogenous and exogenous aspects, together with a detailed division of the avoidable exogenous exergy destruction. Moreover, [77] presents an exergoeconomic analysis. Nitrogen is considered as the closed Brayton working fluid in all three papers.

Fig. 7(b) depicts another version of this type of cycle presented by Salimpour and Zahedi in [78]. In this case, the LNG is used to cool the gas open cycle air intake and as a heat sink of the closed nitrogen Brayton. Also carried out is the direct expansion of the NG previously heated by the gas turbine exhaust gases. This combined cycle system has the special feature of incorporating a regenerator between the closed and open BC. This achieves to increase the temperature of the air before the combustion chamber, with the advantage of increasing efficiency.

Table 5 gives a summary of some references that employ BC based methods for the recovery of LNG exergy.

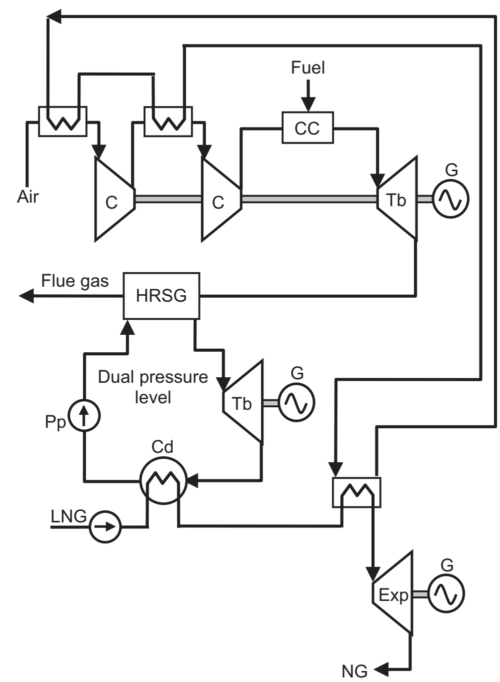

Fig. 8. Schematic configuration of a combined cycle with inlet air cooling, intercooling and LNG cold exergy utilization. C: compressor; CC: combustion chamber; Exp: expander; G: generator; HRSG: Heat recovery steam generator, Pp: pump; Tb: turbine.

3.4. Combined cycles based power plants

The integration of regasification plants with conventional combined cycles, gas turbine and steam RCs, is an option for the LNG cold exergy exploitation studied by several investigators. In these cases, the LNG thermal exergy is used to cool the air at the compressor inlet of the gas cycle and to condense the steam at temperatures below ambient.

Xiaojun Shi et al. propose different alternatives of integrating conventional combined cycles with regasification plants [33,34,79]. Ref. [79], for example, includes an improvement in the performance of a combined cycle power plant based on the use of the LNG cold exergy to cool the intake air, intermediate cooling and steam condensation. This power plant is schematically depicted in Fig. 8. The decrease of the intake air temperature and the intermediate cooling is carried out with a closed pressure water system, which in turn is cooled by LNG. The inlet temperature of the first and second compression stages correspond respectively with 12 and 50 °C. Another important characteristic of the cycle is that the condenser pressure is reduced to 0.015 bar, corresponding to a saturation temperature of 13 °C. Also, the NG pressure exergy is taken advantage of in the direct expansion to generate electricity. The NG is heated to 145 °C before entering the expander, at a pressure of 30 bar with the closed water circuit. The authors compare this thermal power plant with a conventional combined cycle, with the same operating parameters, but without LNG integration and with condensation pressure of 0.045 bar (31 °C saturation temperature). The results in terms of electrical efficiency are 56.53% for the conventional cycle and 59.30% for the proposed cycle.

Other researchers substitute the steam RC of the combined cycle with an organic one with the aim of lowering the condensation temperature and avoiding freezing problems. Qiang et al. in Ref. [80] discuss a gas turbine combined cycle and a R23 organic Rankine Cycle (ORC), with intake air cooling and condensation by LNG. They point out that with an ambient temperature of above 30 °C, a decrease of 10% in compressor inlet temperature results in an output net power increase of about 10 and 2% in the overall performance of the cycle.

Ref. [81] compares various plant configurations associated with LNG regasification and a combined cycle consisting of a gas turbine and a pure ammonia RC is selected to be the best, from the thermoeconomic standpoint.

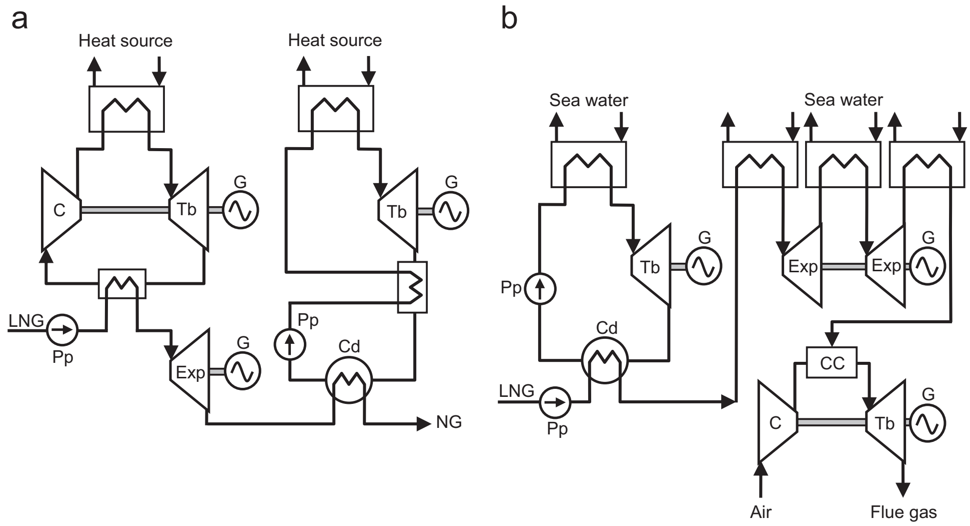

Fig. 9. Schematic configurations of combined cycles consisting of: (a) closed BC, regenerative RC and direct expansion, (b) RC, direct expansion with two stages and reheat and gas open cycle C: compressor; CC: combustion chamber; Exp: expander; G: generator; Pp: pump; Tb: turbine.

Table 6
Summary of different combined cycles for the use of the exergy of LNG.

Cycle type	Working fluid	Heat source	*T* max (°C)	*T* min (°C)	*p* NG (bar)	Thermal efficiency	Exergy efficiency	Ref.
Gas turbine + RC condensation by LNG + direct expansion	Flue gas—steam	Combustion heat	1300	13	3	59.24%	55.62%	[33]
Gas turbine + RC with condensation by LNG	Flue gas—steam	Combustion heat	1350	7	–	55.5%	54.89%	[34]
Gas turbine with inlet air cooling and intercooling + RC with condensation by LNG + direct expansion	Flue gas—steam	Combustion heat	1300	13	3.5	59.30%	54.98%	[79]
Gas turbine with inlet air cooling + RC with condensation by LNG	Flue gas—R23	Combustion heat	1300	−80	–	–	50.00%	[80]
Gas turbine + RC	Flue gas—ammonia	Combustion heat	1026	−25	91	46.60%	–	[81]
BC + RC + direct expansion	N_2—(ammonia + water)	–	390	−40	1.5	53.08%	60.94%	[82]
RC + direct expansion + gas turbine	Propane—flue gas	Sea water—Combustion heat	1200	−40	–	35.84%	–	[83,84]

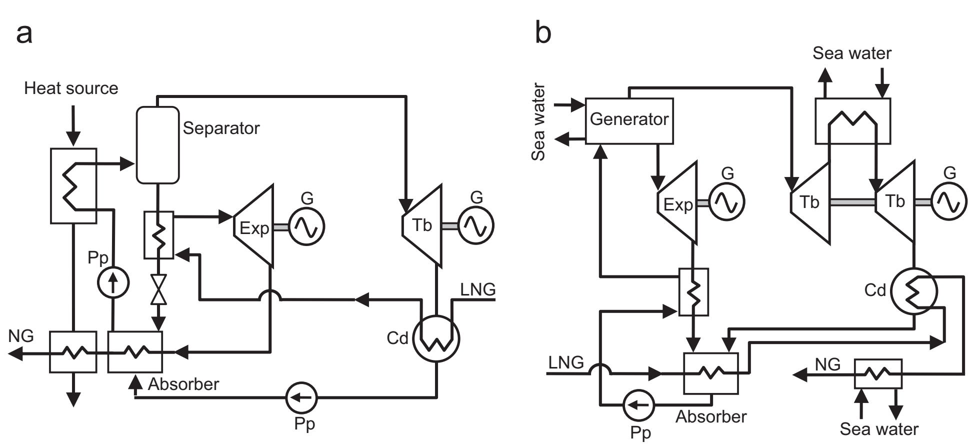

Fig. 10. Schematic configurations of the Kalina cycle: (a) ammonia–water as working fluid, (b) Tetrafluoromethane-propano as working fluid. Exp: expander; G: generator; Pp: pump; Tb: turbine.

Besides the combined cycles, other configurations among Brayton and Rankine cycles have also been proposed, such as that shown in Fig. 9(a) [82]. Another case is presented in [83,84] by Najjar, where the LNG is regasified in the condenser of a propane RC and is expanded in two stages with intermediate reheating before entering the combustion chamber of a open gas cycle (see Fig. 9(b)). A more complex system is proposed in [85], consisting of an open BC where the sensible heat of the gas turbine exhaust gases is recovered in a steam RC and the latent heat in an ORC and of heating the NG to then expanding it.

A summary of the works based on combined cycles for the recovery of LNG exergy is presented in Table 6.

3.5. Kalina cycle based power plants

Kalina [86] developed a new power cycle that uses a solution of different vaporization points as the working fluid. The Kalina cycle shows a greater exergetic efficiency than an ORC because the temperature profile of the mixture is closer to the heat source temperature [87,88]. Shi and Che propose the combination of an ammonia–water Kalina cycle and LNG regasification, where the LNG cold energy is used to condense the ammonia at the turbine outlet and to cool the absorber [36]. Furthermore, the cycle incorporates the direct expansion method. This proposed power plant is shown in Fig. 10(a). In a later study, these authors, together with Wang, perform a thermodynamic optimisation of this same combined cycle, using the differential evolution algorithm [89].

Another configuration based on the Kalina cycle is presented by Liu and Gua in Ref. [37] and corresponds with the schematic diagram in Fig. 10(b). In this case, the binary mixture is tetrafluoromethane (CF_4) and propane (C_3H_8). This thermal cycle is compared with a propane ORC, with the same top temperature and −75 °C as the minimum temperature. The findings are that the proposed Kalina cycle has an efficiency of 9.4% more than the propane ORC.

A summary of the characteristics of the cycle data is given in this section, shown in Table 7.

3.6. Power plants with CO_2 capture

Apart from the integrating of LNG regasification to improve power plant efficiency, CO_2 capture can also contribute to the design of a near zero emissions power plant.

CO_2 capture can be performed with three different technologies, namely: post-combustion capture systems, pre-combustion capture systems and oxy-fuel capture systems [90]. But the three methods greatly penalise the energy efficiency of the plant, which ranges between 10 to 28% for plants that consume NG as a fuel [91].

In power plants with LNG exergy exploitation, it is common to use the oxy-combustion method. This is based upon combusting, with a small amount of higher than stoichiometric oxygen (produced in an air separation unit) and recirculating the flue gases to reduce the temperature. This technique avoids the formation of NO_x and only CO_2 and water steam is obtained as combustion products. Deng et al. [38] proposed a RC operating under this concept and capture the CO_2 using the LNG cold energy. The proposed system is shown in Fig. 11(a). Flue gases are used as the RC working fluid. CO_2 capture is performed after the condenser in a liquid state at a pressure of 5.3 bar.

The obtaining of CO_2 in an already liquid state is a major advantage over power plants that use this oxy-combustion technology without the contribution of the LNG exergy as they require a CO_2 liquefaction system for subsequent storage, resulting in a considerable loss of efficiency [90].

Table 7
Summary of different Kalina cycles for the use of the exergy of LNG.

Cycle type	Working fluid	Heat source	*T* max (°C)	*T* min (°C)	*p* NG (bar)	Thermal efficiency (%)	Exergy efficiency	Ref.
Kalina cycle + direct expansion	Ammonia (50%)–water (50%)	Low temperature waste heat	150	−54	3	33.28	48.87%[a]	[36]
Kalina cycle + direct expansion	Ammonia (52%)–water (48%)	Low temperature waste heat	134	−66	3	39.33	55.62%[a]	[89]
Kalina cycle	CF_4 (73%)–C_3H_8 (27%)	Seawater	10	−65	30	23.50	–	[37]

[a] In this case the exergy efficiency is defined as the exergy output (net work and exergy of the city gas) divided by the exergy input.

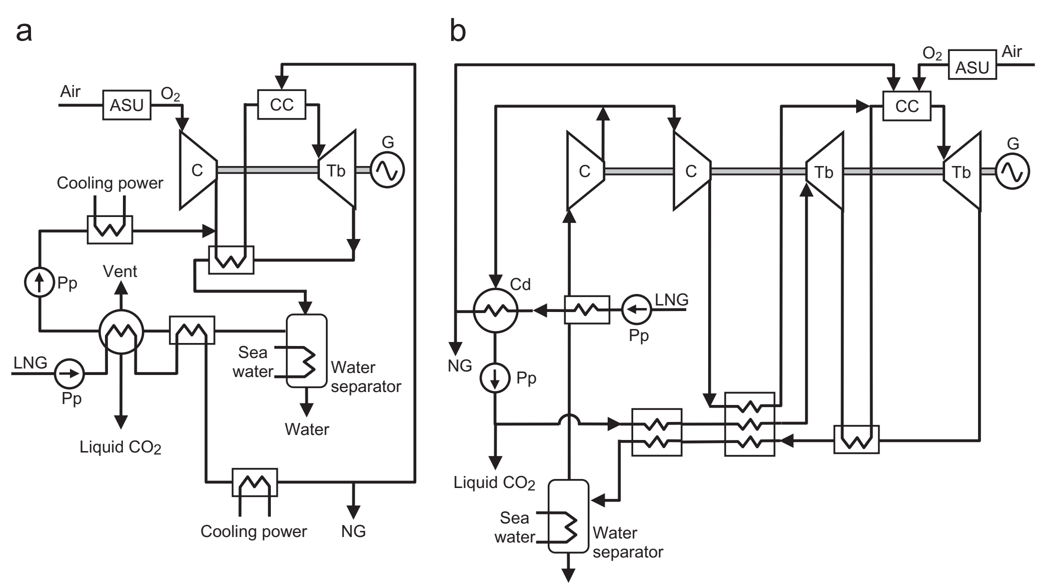

Fig. 11. Schematic configurations of cycles with CO_2 capturing: (a) using a RC, (b) using a quasi-combined cycle mode with a supercritical CO_2 Rankine-like cycle and a CO_2 Brayton cycle. ASU: air separation unit, C: compressor; CC: combustion chamber; Exp: expander; G: generator; Pp: pump; Tb: turbine.

Table 8
Summary of cycles with capture CO_2 employing exergy of LNG.

Cycle type	Working fluid	Heat source	*T* max (°C)	*T* min (°C)	*p* NG (bar)	Thermal efficiency (%)	Exergy efficiency	Ref.
RC	CO_2	Oxy-fuel Combustion	1250	−53	70	71.04	50.53%	[38]
RC (COOLCEP-S)	CO_2	Oxy-fuel Combustion	900	−50	70	59.10	39.80	[92]
RC (COOLCEP-C)	CO_2	Oxy-fuel Combustion	900	−50	70	51.60	37.30%	[94]
Quasi-combined Rankine Brayton	CO_2	Oxy-fuel Combustion	1300	−70	30	65.50	51.60%	[95]

Table 9
Osaka Gas's history of LNG exergy utilization.

Year	Utilization
1977	Air separation (not existing)
1979	Power generation: propane RC
1980	Carbon dioxide liquefaction
1982	Power generation (propane RC+direct expansion)
1983	Air separation
1987	Cold source for the chemical industry
1993	Air separation
1997	Boil off re-liquefaction system with cold energy storage
2004	Cooling of intake air for gas turbine
2010	Cascade LNG cold energy in a industrial complex

Zhang et al. pose new power systems, taking as reference the cycle proposed by Deng et al. and carry out changes based on the turbine backpressure and the arrangement of the LNG vaporizers. They refer to these new cycles with the acronym of COOLCEP meaning “cool clean efficient power” and develop two configurations: COOLCEP-S [92,93] and COOLCEP-C [94].

The main difference between the two configurations is the turbine discharge pressure. In the COOLCEP-C version, expansion is performed to near atmospheric pressure and then the CO_2 is compressed up to condensation pressure with a pre-cooling by the LNG. In the COOLCEP-S version, the pressure at the turbine outlet corresponds with the CO_2 saturation pressure at −50 °C, which is 6.8 bar.

More complex power plants were proposed by Zhang and Lior [95–97] working under a quasi-combined cycle with a supercritical RC and BC, which are interconnected with each other through the BC recovery process and the working fluid which is the same in both cycles, CO_2. The configuration of this quasi-combined cycle is depicted in Fig. 11(b).

A summary of the most prominent parameters of the cycles mentioned in this section is shown in Table 8.

4. Existing regasification plants with LNG exergy exploitation

The first regasification plants with LNG exergy exploitation were developed in Japan in the late 70s, and this continues to be the country that most exploits it today. The first application was developed in air separation technology in 1977 on the Senboku terminal, followed by cryogenic power generation in 1979, with a 1450 kW propane RC in this same terminal [25]. The Japanese company, Osaka Gas, owner of Senboku I, Senboku II and Himeji LNG terminals, is one of the pioneers in exergetic exploitation during LNG regasification. Tables 9 and 10 respectively show a record of Osaka Gas' LNG exergy usage [25,98] and an overview of the cryogenic power plants in Japan [85,99].

In Europe, Enagás, the main NG transportation company in Spain, is the pioneer in installing plants generating electric energy by making use of the LNG cold exergy. A RC of 4.5 MW is installed in their Huelva terminal, using sea water as a heat source. The installation has been in operation since April 2013 with an investment of 13 million [100]. Enagás also has a feasible project to install a plant for generating electrical energy by NG direct expansion of 5.5 MW in its LNG terminal in Barcelona [101].

In France, the LNG regasification plant, Fos-Tokin, and its neighbouring company, Air Liquide, combine synergies to improve the efficiency of both plants [102]. Other European terminals, such as South Hook (UK), Zeebrugge (Belgium) or Montoir de Bretagne (France), perform LNG regasification with the exhaust gases from a combined cycle. This practice is correct from the environmental standpoint, to avoid localised cooling of seawater, but from the energy efficiency viewpoint it could be improved, for example, by installing a RC or BC with exhaust gases as the energy source and the LNG regasification process as the heat sink. Such practice prevents the cooling of the seawater and also reduces CO_2 emissions as electricity is generated without an extra fuel supply.

An example of integration between a combined cycle and a LNG terminal is the EcoEléctrica Company located in Peñuelas (Puerto Rico). LNG vaporization is performed via glycol that is heated by the gas turbine intake air [103]. Thus, the compressor suction temperature is reduced to below atmospheric, which, in this region is high and causes a decrease in the efficiency of the combined cycle.

It can be concluded that the LNG regasification process has a high exergetic value and can be exploited for different applications, the most common being power generation. The decision to install a specific type of power plant is conditioned by the needs, restrictions and characteristics of the regasification plant, taking into consideration the advantages and disadvantages of each type shown in Table 11. Nonetheless, it is essential for each regasification plant to carry out a technical-economic study to determine the feasibility and profitability of the installation to be implemented.

5. Conclusions and future works

The current state of the thermodynamic cycles which use LNG exergy to increase the efficiency of power plants is reviewed in this paper. The following observations are obtained from> the study:

- LNG possesses a high exergetic power from being in cryogenic conditions. In the conventional gasification processes with seawater vaporizers or submerged combustion, this LNG exergy is not recovered. In addition, power consumption is required to obtain the NG.
- The LNG exergy is twofold: thermal and mechanical. To exploit the mechanical exergy, one single method is used, which is direct expansion of the LNG. However, the thermal side allows more options. It can be recovered in the RC, BC and the Kalina cycles as a heat sink and as extra input of exergy. It can also contribute to CO_2 capture to design a power plant with almost zero emissions.
- If the heat source is the environment (water or air), or another source of low-grade heat, the RC is best suited, while the BC is

Table 10
Cryogenic power plants in Japan.

Company	Terminal	Start of operation	Type cycle	Power (kW)	LNG flow rate (t/h)	*p* NG (bar)
Osaka Gas	Senboku	1979	RC	1450	60	30
Toho Gas	Chita Kydo	1981	RC	1000	40	14
Osaka Gas	Senboku	1982	RC+direct expansion	6000	150	17
Kyushu	Kitakyusyu LNG	1982	RC+direct expansion	9400	150	9
Chubu Power	Chita LNG	1984	RC+direct expansion	2 × 7200	150	9
Touhoku Power	Niigata	1984	Direct expansion	5600	175	9
Tokyo Gas.	Negishi	1985	RC	4000	100	24
Tokyo Power	Higasi Ougishima	1986	Direct expansion	3300	100	8
Osaka Gas	Himeji	1987	RC	2500	120	40
Chubu Power	Yokkaichi	1989	RC+direct expansion	7000	150	9
Tokyo Power	Higasi Ougishima	1991	Direct expansion	8800	170	4
Osaka Gas	Himeji	2000	Direct expansion	1500	80	15
Osaka Gas	Senboku	2004/2010	Cooling of intake air for gas turbine	1100 MW	–	–

Table 11
Summary the advantages and disadvantages the different types of power plants with LNG exergy exploitation.

Power plant type	Advantages	Disadvantages
Direct expansion	– Simple structure – Implementation in real cases	– Low efficiency – Only the mechanical exergy of LNG is exploited
RC / RC+direct expansion	– Simple structure – Implementation in real cases – Appropriate when a low temperature heat sources are available	– Limited efficiency due to the temperature range of the application of the working fluid – The condensation temperature is higher than the normal boiling point of the working fluid
Rankine cycles combination	– The operating temperature range is greater when compared with that of a single RC	– Complex structure – High cost – There are no actual plants implemented
Gas open cycle (cooling air inlet)	– The compression work is reduced	– Efficient only during warm seasons or in areas with an elevated ambient temperature
Closed BC / Closed BC+direct expansion	– High efficiency – Simple structure – A wide temperature range for the application of the working fluid – The reduction of the irreversibilities in the heat transfer between the working fluid and the LNG in comparison with a RC	– Only three working fluids are able to function under this cycle's conditions – It is not appropriate for the recovery of residual low grade heat – There are no actual plants implemented
Brayton cycles combination	– High efficiency – High power output to the LNG mass rate	– Complex structure – High cost – There are no actual plants implemented
Combined cycles	– High efficiency – High power output to the LNG mass rate	– Complex structure – High cost – There are no actual plants implemented – High vacuum in the condenser when a steam RC is used in the bottoming cycle
Kalina cycle	– More exergetic efficiency than an ORC	– Limited efficiency due to the temperature range of the application of the working fluid – Complex structure – There are no actual plants implemented
With CO_2 capture	– Power plant with almost zero emissions – The cycle's maximum temperature is not limited by the working fluid (CO_2)	– Complex structure – An air separation unit is needed – High cost – There are no actual plants implemented

most appropriate when an intermediate or high grade source is available.

– When using a high temperature heat source, the combination of BC, RC and direct expansion is most favourable to achieve good efficiency. This type of configuration allows operating with a wider temperature range and also makes use of the LNG mechanical exergy.
– Ethane and ethylene are presented as the fluids best suited to operate in the RC with sources of low temperature heat. If the temperature is higher, one of the best fluids is CO_2. The use of zeotropic mixtures, such as the ammonia–water binary pair, results in a reduction of irreversibilities in the heat transfer due to having a variable temperature in the vaporization and condensation. With regard to the BC working fluids, it is beneficial they have the lowest possible critical point. Also, the closer the cycle operates to the critical point, the better the performance achieved. Helium and nitrogen are presented as the most suitable working fluids.

– As regards existing regasification plants that exploit LNG exergy, Japan is the pioneer and the greatest exploiter of this resource. In Europe, the first company was Enagás with a 4.5 MW with a RC, using sea water as the heat source.

The purpose of this review work is to open fresh research paths which allow for the creation of new power plant structures, differing from the traditional structures in their design and increased efficiency. In order to accomplish this, the authors are studying the Brayton and Rankine cycles arranged in series with regard to the power source allowing for an improved exergetic exploitation of the LNG and an overall increase in efficiency. The results obtained from this study have been sent to a publisher.

Future works should also be aimed at the optimisation of the power plants. For this reason, an economic study, in addition to one regarding the plant's design, must be carried out. Therefore, the power plants' new structures, the design of their equipment, the integration of alternative energy sources and an economic study are important issues which must be addressed in the future.

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